The case for dark matter self interactions

Kai Schmidt-Hoberg

Material from 1504.06576 and 1308.3419
with F Kahlhoefer, J Kummer, M Frandsen and S Sarkar

2016-06-22: Theoretical Particle Physics (DESY - Europe) **[Deadline: 2016-08-05]**
Junior - hep-ph, hep-th

Higgsino dark matter and naturalness

cf talk by Olive and Ruiz-Femenia

1 TeV Higgsino nice dark matter candidate (no tuning for relic abundance)

Higgsino mass ~ μ (from term in the superpotential) cf talk by Munoz

Electroweak vev determined by SUSY parameters

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

Need cancellations for large μ → unnatural

$$\Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p} = \frac{p}{v^2}\frac{\partial v^2}{\partial p} \qquad \Delta_\mu \sim \frac{2\mu^2}{M_Z^2}$$

~ 250

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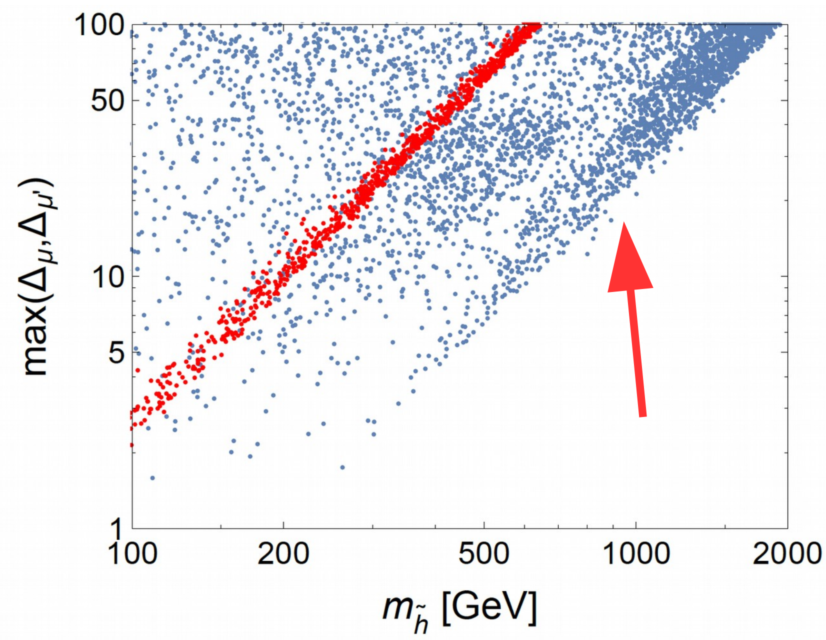
~ 250

There can be a soft contribution to the Higgsino mass (which nobody writes down)

Ross, KSH, Staub, 1603.09347



Back to SIDM → Motivation: Cosmology

- The collisionless cold dark matter paradigm fits perfectly at large scales
- There are however various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:

  – Cusp-vs-core problem — Moore (1994), Flores, Primack: astro-ph/9402004

  – Missing-satellite problem — Klypin et al.: astro-ph/9901240, Moore et al.: astro-ph/9907411

  – Too-big-to-fail problem — Boylan-Kolchin, Bullock, Kaplinghat: 1103.0007, 1111.2048

DM self-interactions may solve some (or all) of these problems — Spergel & Steinhard: astro-ph/9909386

Aarsen, Bringmann, Pfrommer, 1205.5809
Dasgupta, Kopp, 1310.6337
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But it's clearly all **baryons**, as sho… in 1602.x…

But **baryons** clearly cannot do it, see 1602.yyyyy!

More details in next talk by Basudeb!

…s, Prim…

Klypin et al.: a… …h/9901240

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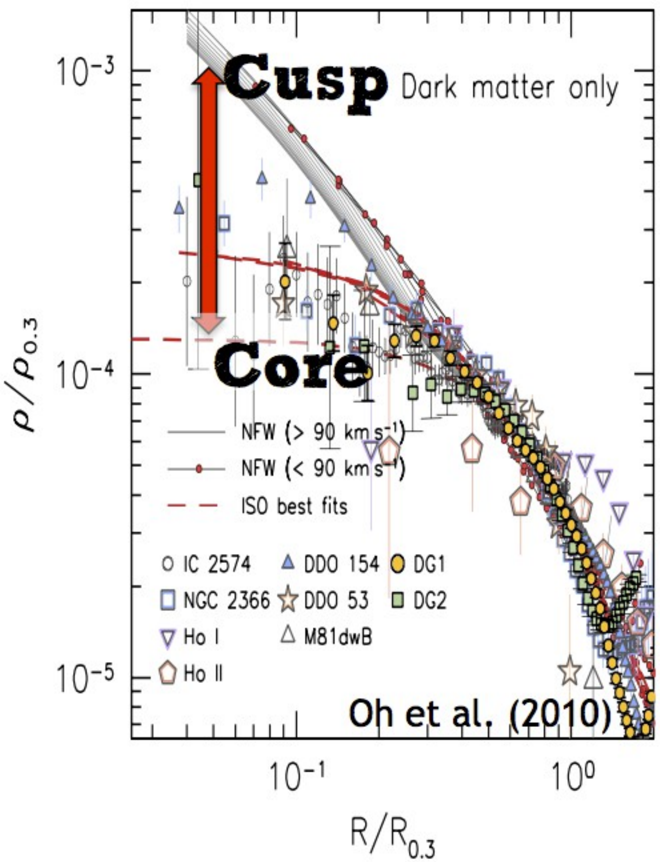
DESY erc

Does DM have Interactions?

Core-Cusp



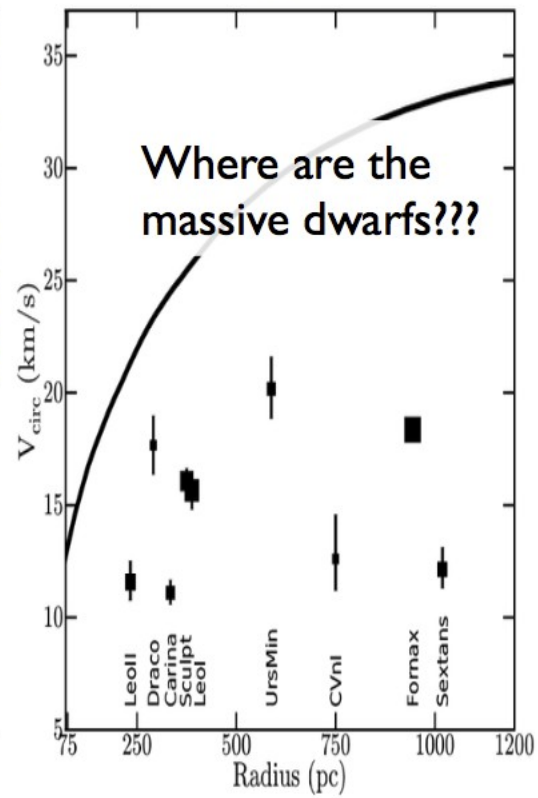
Moore (1994);
Flores and Primack (1994)

Missing Satellites

Klypin, Kravstov, Valenzuela, and Prada (1999)

Most massive satellites predicted denser than observed

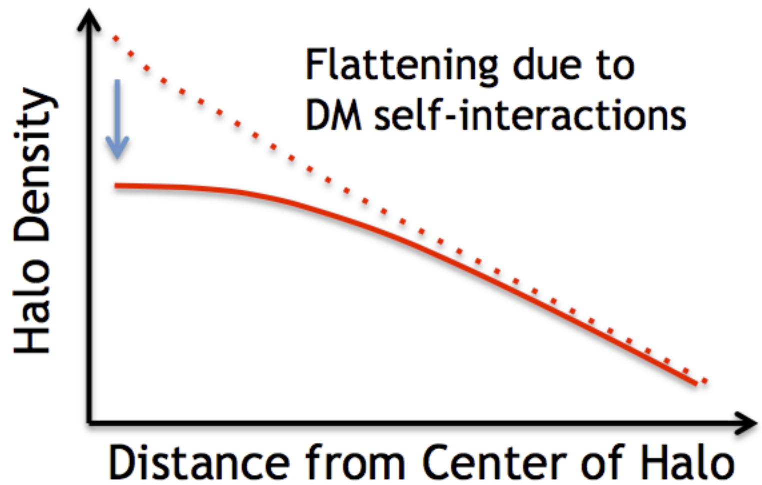
Too Big to Fail

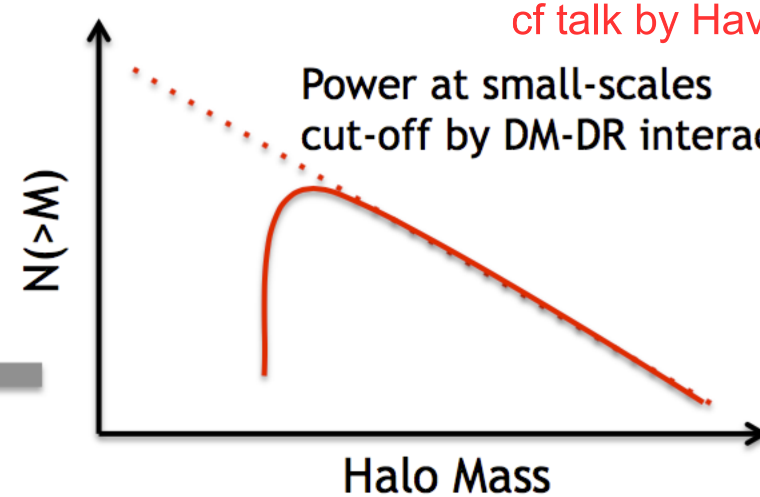


Boylan-Kolchin, Kaplinghat, Bullock (2010)

Simultaneous Solutions to Small Scale Structure Problems of Lambda-CDM

cf talk by Havard





Too-Big-to-Fail Problem and the Core-Cusp Problem solved using DM self-interactions that smoothen DM density

Spergel and Steinhardt (1999)

Talk by Kai Schmidt-Hoberg

Missing Satellites Problem solved using DM interactions with a radiation-like species that delays kinetic decoupling

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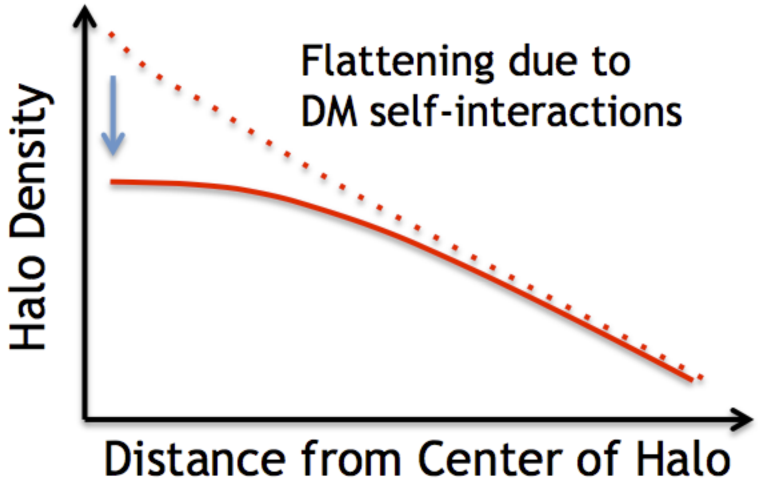
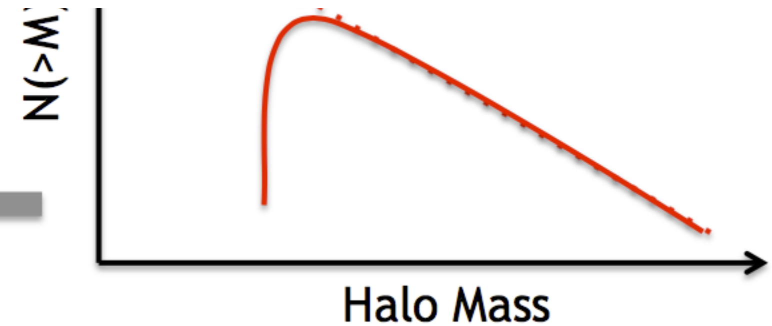


cf talk by Havard

$$M_{\rm cut} \approx \frac{4\pi}{3}\frac{\rho_\chi(T_{\rm kd})}{H(T_{\rm kd})^3} \approx 7\cdot 10^{10} M_\odot \left(\frac{T_{\rm kd}}{100 eV}\right)^{-3}$$



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Two Types of Models

See Bringmann et al. (2016) for EFT-type treatment
Hannestad++ (2015, 2016) for Pseudo-scalar mediators
…
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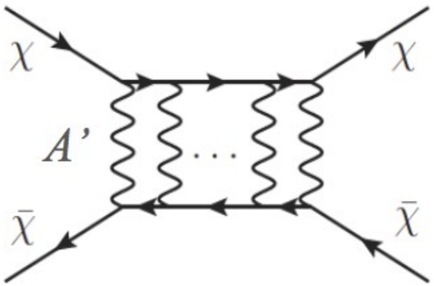
DM Self-Interactions

DM-DR Interactions

DM + (Sterile) Neutrinos + A'



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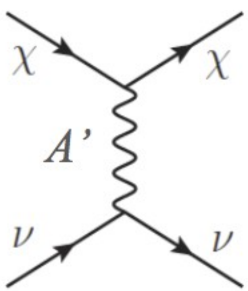

DM-Neutrino Interactions

van den Aarssen, Bringmann, Pfrommer (PRL, 2012)
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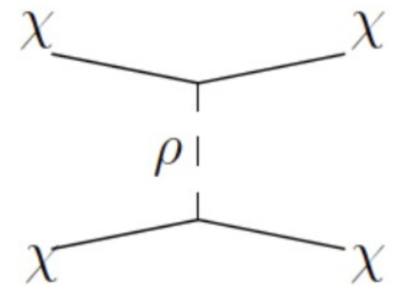
Pseudo-Dirac DM + Complex Scalar



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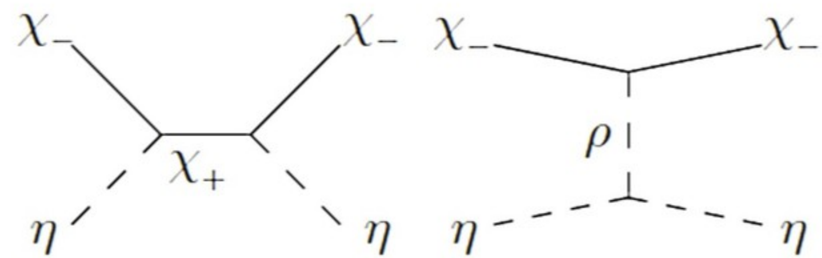

DM-Goldstone Interactions

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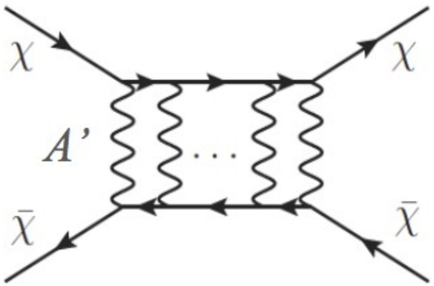

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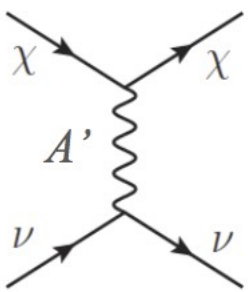

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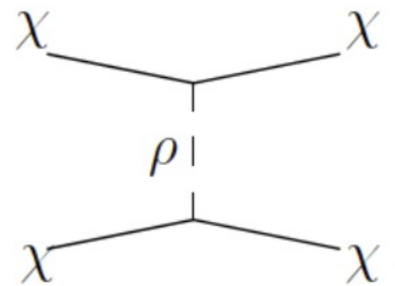

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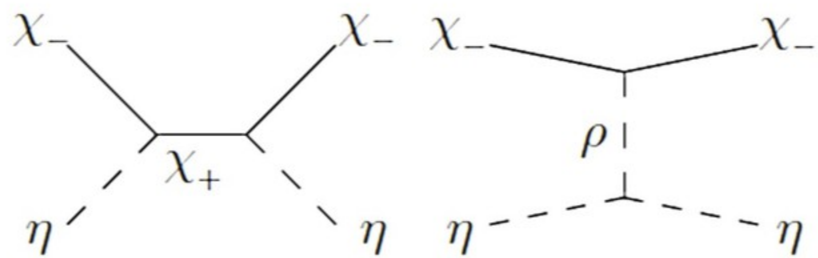

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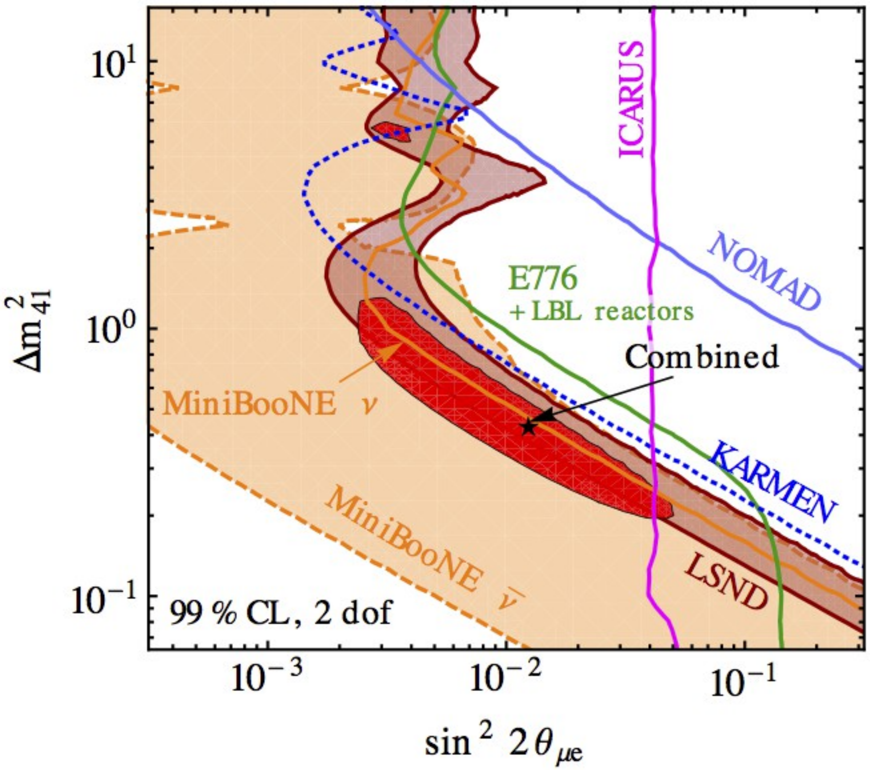
Sterile Neutrinos at 1eV



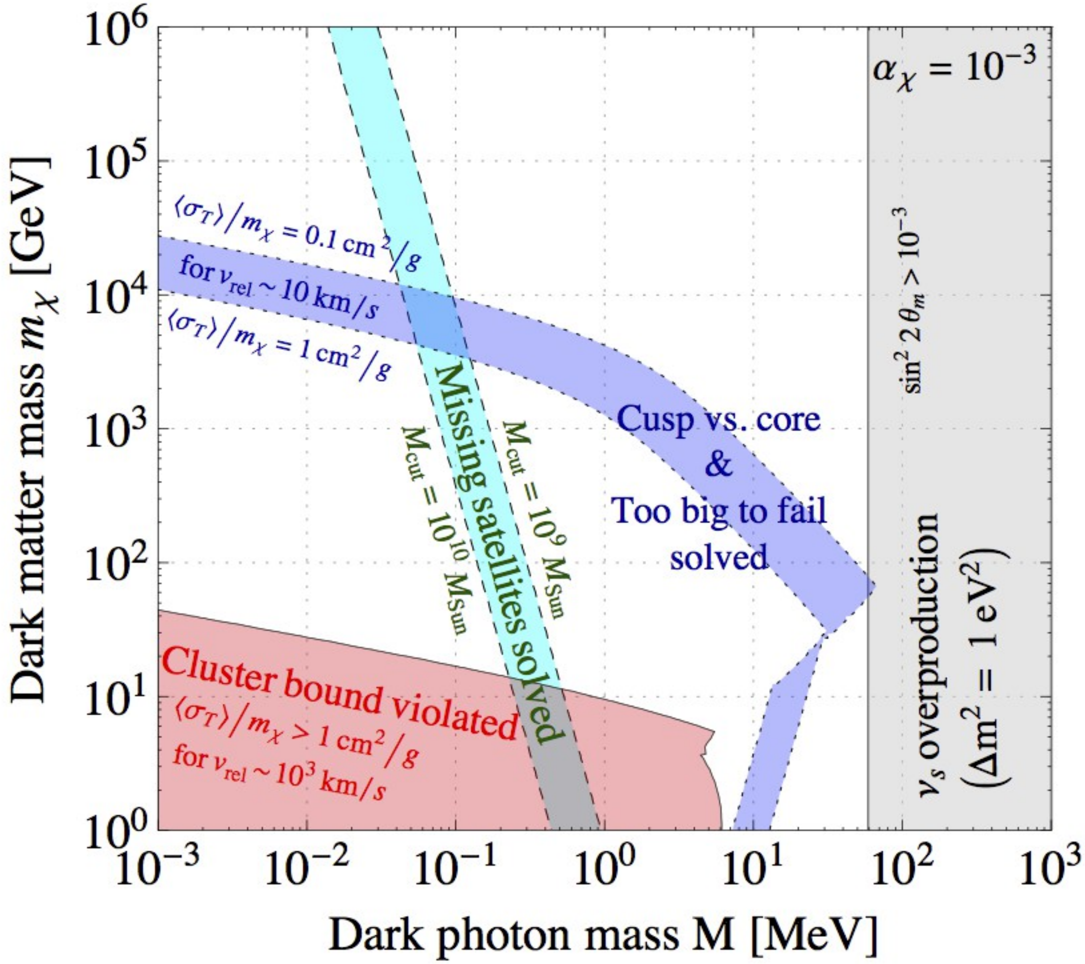
Global fit to all appearance data is consistent, and 3+2 or 1+3+1 models are better fits than 3 only or 3+1.

Machado, Kopp, Maltoni, Schwetz (2013)

+ similar results by
Palazzo;
Giunti, Laveder, et al;
Conrad et al., …

If one takes the neutrino oscillation anomalies seriously, one needs 1 or 2 sterile neutrinos with large mixings

DM-Neutrino Concordance



One can explain N_{eff} , Neutrino Oscillations, and All 3 DM problems, simultaneously

Dasgupta and Kopp (2014). See also Bringmann, Hasenkamp, Kersten (2014)

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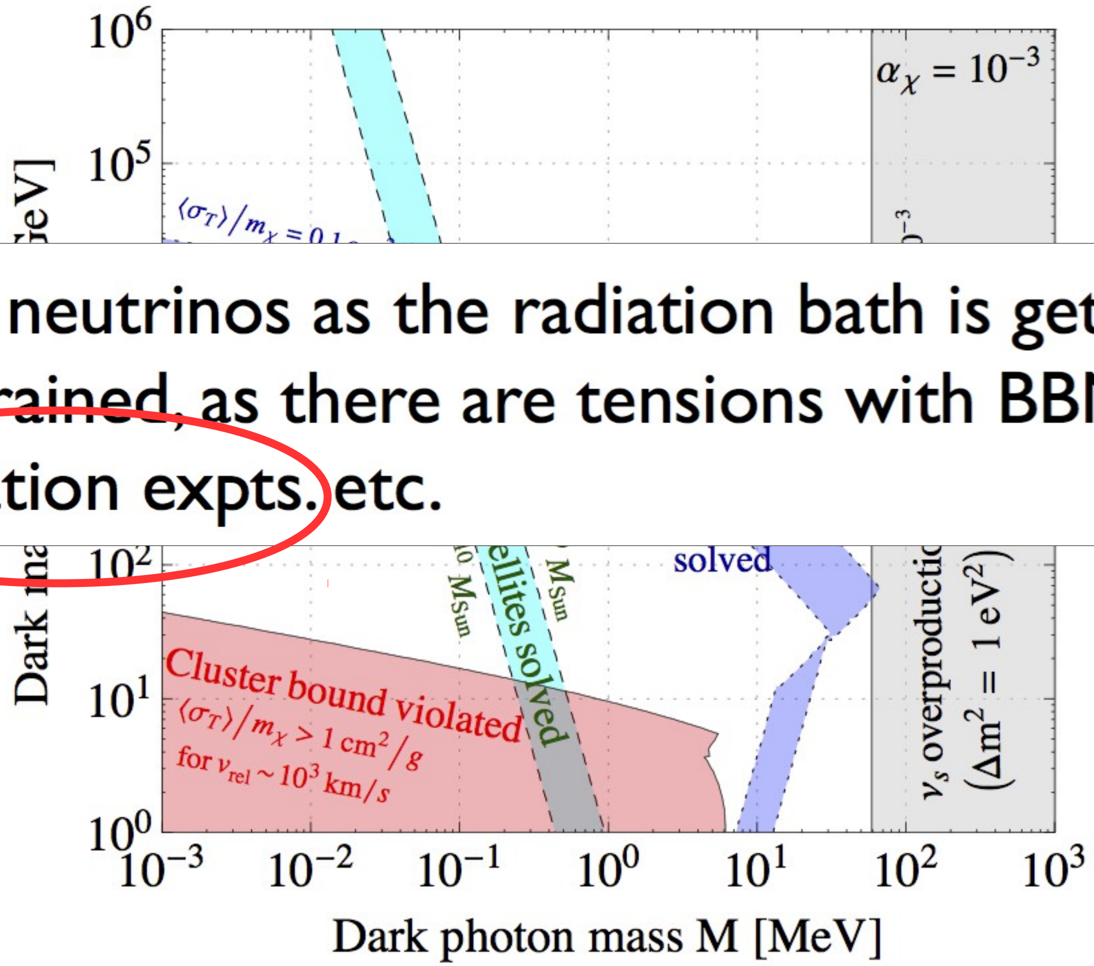

Using neutrinos as the radiation bath is getting constrained, as there are tensions with BBN, CMB, oscillation expts. etc.

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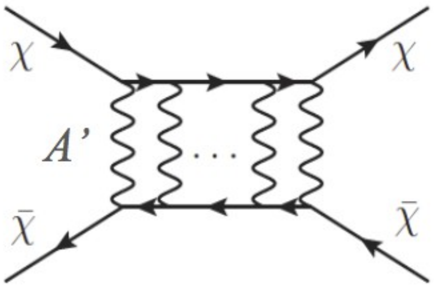

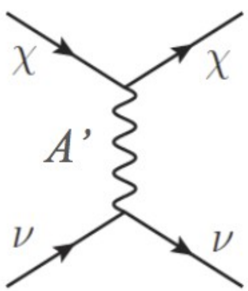

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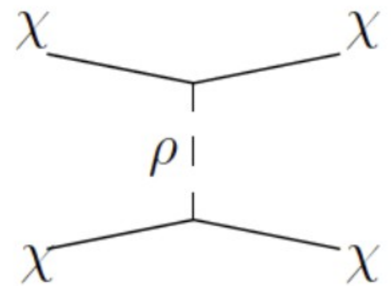

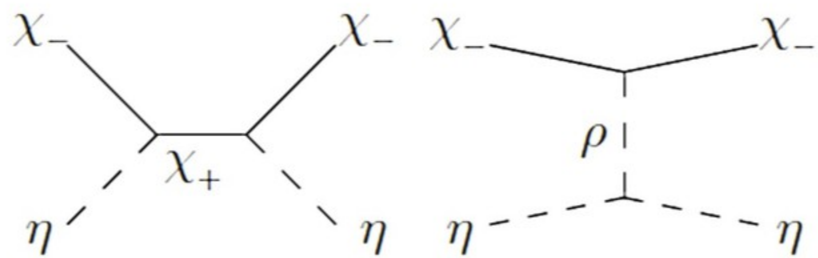

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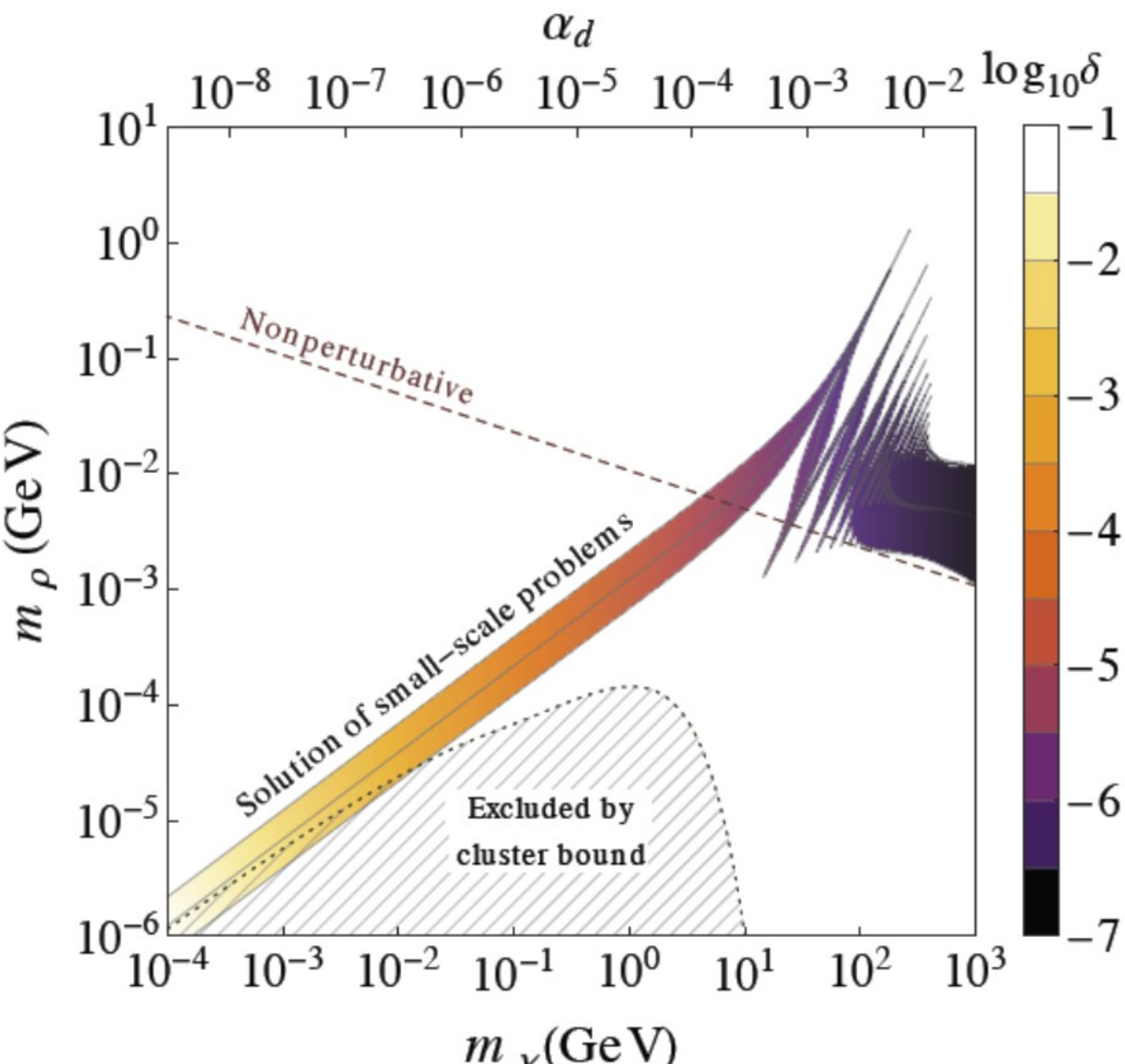
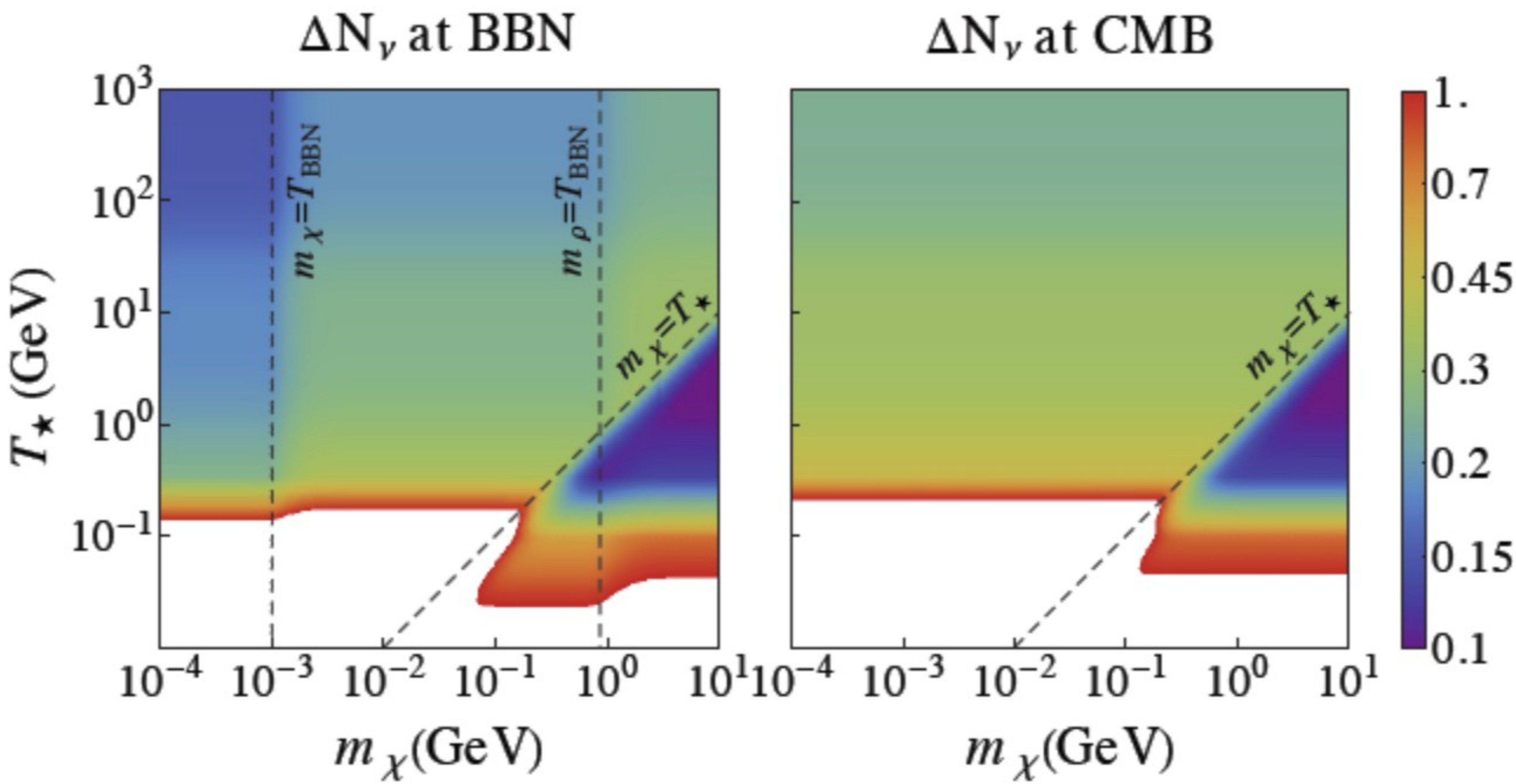
Solving Small-Scale Problems



Chu and Dasgupta, 2014 (PRL)

Dark Radiation Predictions



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dNeff > 0.1 is detectable using EUCLID, via lensing of the CMB

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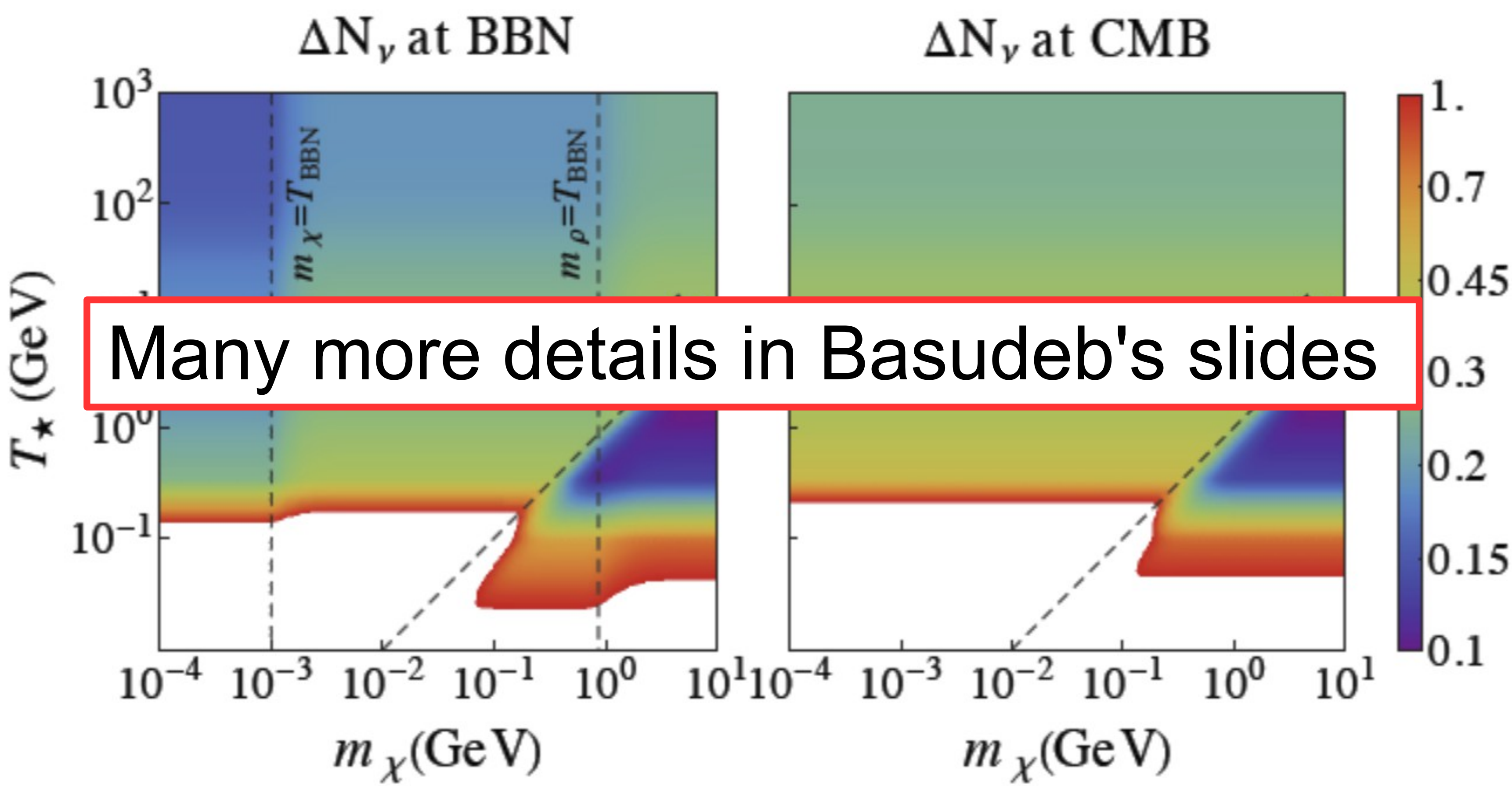

Many more details in Basudeb's slides

Chu and Dasgupta, 2014 (PRL)

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Motivation: Particle physics

- Dark sector often assumed to be simple, mainly because we don't know much…

- Large self-interactions are natural in models with a complex dark sector (e.g. with a new gauge group), or light mediators, e.g.
  - Strongly interacting DM — Kusenko, Steinhardt: astro-ph/0106008
  - Mirror DM — Berezhiani, Dolgov, Mohapatra: hep-ph/9511221; Mohapatra, Nussinov, Teplitz: hep-ph/0111381
  - Atomic DM — Kaplan, Krnjaic, Rehermann, Wells: 0909.0753; Cyr-Racine, Sigurdson: 1209.5752

- Bonus: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.

How large a cross section?

- To be observable on astrophysical scales, self-interaction cross sections have to be large, typically

$$\sigma / m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns}/\mathrm{GeV}$$

- The nucleon nucleon scattering cross section ~20b at low energies
- The typical cross section of a WIMP is 20 orders of magnitude smaller!

- Potential impact:

  Evidence for DM self-interactions on astrophysical scales would rule out most popular models for DM, such as supersymmetric WIMPs, gravitinos, axions…

Constraints on self-interactions

- Various astrophysical observations give constraints on SIDM:
  - Bullet cluster

    Clowe et al astro-ph/0608407
    Randall et al 0704.0261

    cf talk by Clowe

  - Subhalo evaporation rate

    Gnedin, Ostriker: astro-ph/0010436

  - Halo ellipticity

    Miralda-Escude (2002)

  - Core density in clusters and dwarfs

    Yoshida et al.: astro-ph/0006134
    Dave at al.: astro-ph/0006218

- (Some of) these constraints seemed to be very strong, implying $\sigma/m_\chi < 0.1$ cm^2/g, which is too small to give observable effects
- Constraints apply for particular velocities and can be easily evaded by assuming a velocity dependence of the cross section

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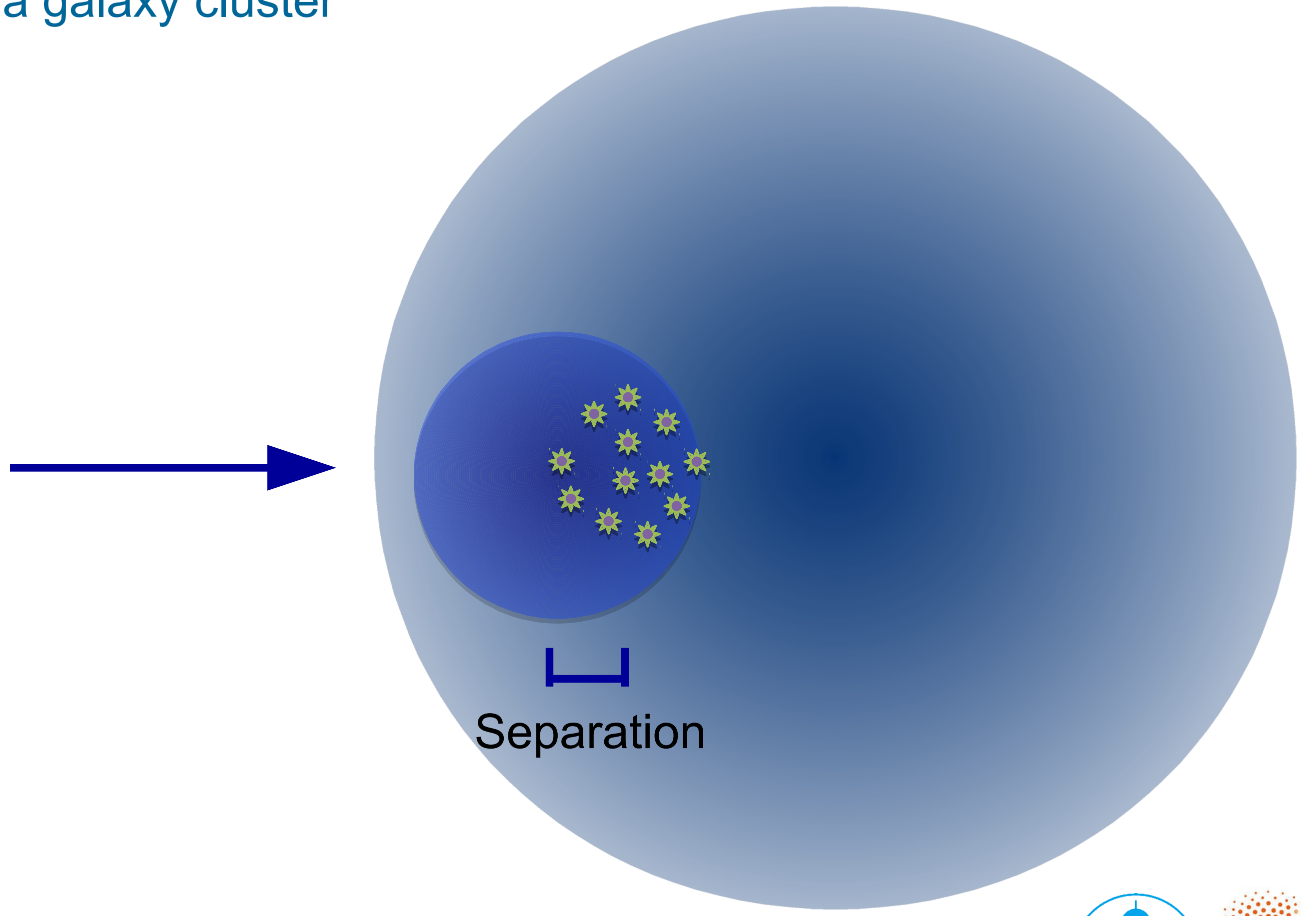
More recent numerical simulations indicate that the conventional bounds on DM self-interactions have been significantly overstated

Velocity-independent DM self-interactions with $\sigma/m_\chi \sim 1\ \mathrm{cm^2/g}$ may still be viable.

Rocha et al.: 1208.3025
Peter et al.: 1208.3026

Smoking gun?

- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster



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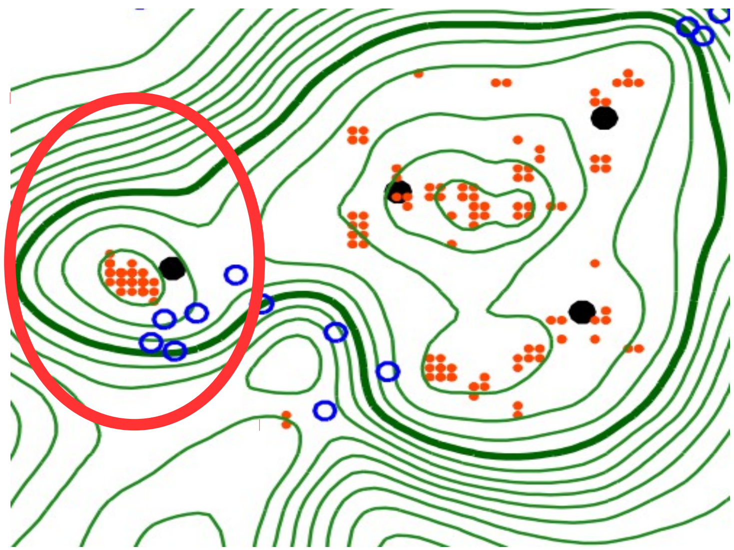
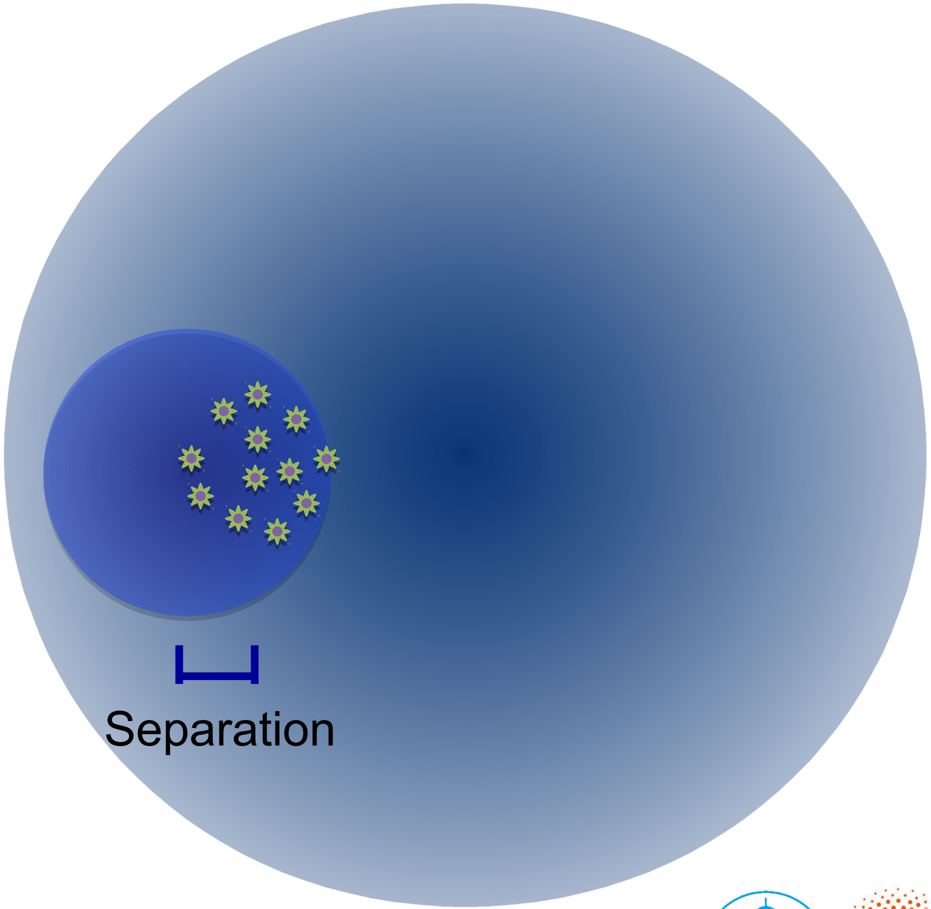




- Recently been **observed in A3827**

Evidence in Abell 3827?

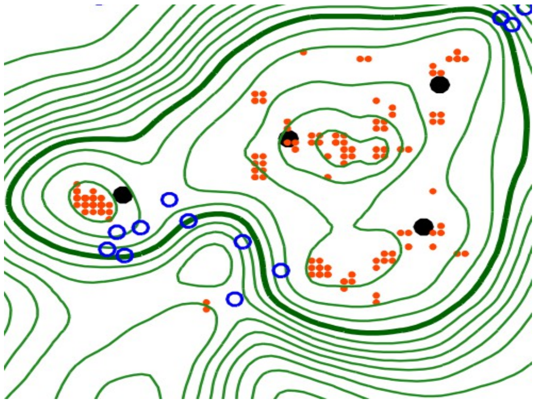
The behaviour of dark matter associated with 4 bright cluster galaxies in the 10kpc core of Abell 3827

Massey et al., arXiv:1504.03388

"The best-constrained offset is 1.62+/-0.48kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. […] if interpreted solely as evidence for self-interacting dark matter, this offset implies a cross-section

$$\sigma/m \sim (1.7 \pm 0.7) \times 10^{-4} \left(\frac{t_{\rm infall}}{10^9 \text{ yrs}} \right)^{-2} \text{cm}^2/\text{g}.$$

where t is the infall duration."



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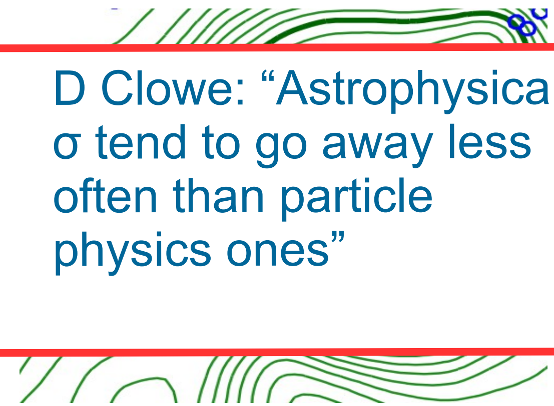

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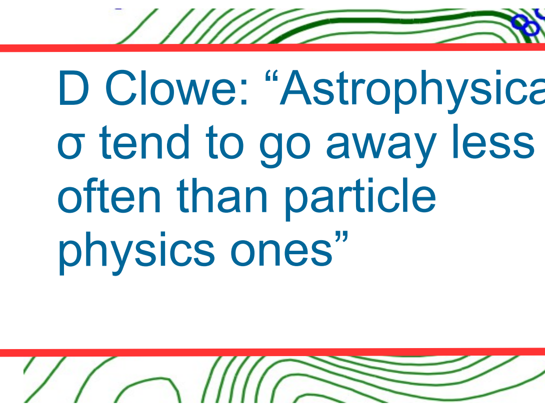

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Two arguments for this unique sensitivity:

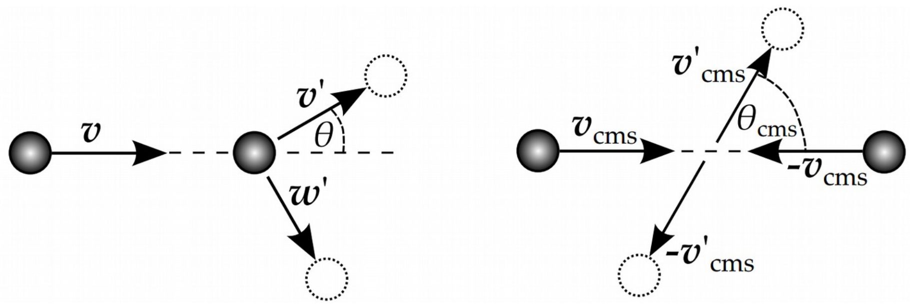
1. A3827 is strongly lensed, allowing for a much more precise measurement of the separation
2. The subhalo under consideration has been falling towards the centre of A3827 for a very long time, so self-interactions have had plenty of time to affect the trajectory of the subhalo

Evidence in Abell 3827?

What has been neglected in this simplistic analysis?

- The stars and the DM subhalo are assumed to develop completely independently, i.e. even a tiny difference in the acceleration can lead to sizeable differences in their trajectories.
  - This neglects the crucial fact that initially the stars are gravitationally bound to the DM subhalo and can only be separated from it if external forces are comparable to the gravitational attraction within the system.
- The effective drag force on the DM subhalo is assumed to be constant throughout the evolution of the system.
  - However the rate of DM self-interactions depends both on the velocity of the subhalo and the background DM density, both of which will vary along the trajectory of the subhalo.
- So how to do a better estimate? Think about the type of self interaction first...

The particle physics picture



The momentum transfer in a collision of two DM particles is completely fixed by the scattering angle. Averaging over many DM particles, the effective momentum transfer is given by

$$\sigma_T = 4\pi \int_0^1 \mathrm{d}\cos\theta_{\rm cms}\,(1-\cos\theta_{\rm cms})\,\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\rm cms}}$$

This is the quantity typically studied

However, this is not all that matters…
Can be obtained with **rare scatters and large momentum transfer** (e.g. isotropic scattering) or **frequent scatters with small momentum transfer** (e.g. long range interactions)

Frequent interactions

- Frequent DM self-interactions imply many scatters for all particles and therefore lead to a deceleration of the overall DM halo.

- This deceleration can be described in terms of an effective drag force

$$\frac{F_{\rm drag}}{m_{\rm DM}} = \frac{\tilde{\sigma}}{4\, m_{\rm DM}} \rho\, v_0^{2m}$$

m = 1 for velocity-independent interactions

m = -1 for long-range interactions

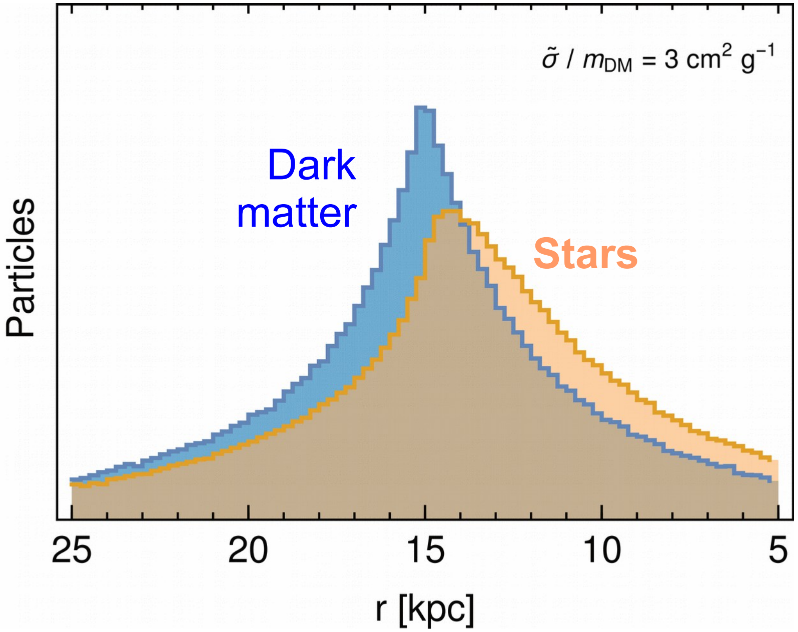
Long range interactions which would give a sizable effect at v~1000 km/s are strongly constrained by low-velocity systems (one could imagine a cutoff due to finite mediator mass though…)

Expectations for frequent interactions

- In the presence of a drag force, a DM subhalo falling into a galaxy cluster will retain its shape, since the drag force affects all DM particles equally.
- In the decelerating frame of the DM subhalo, stars will experience a fictitious accelerating force.
- The resulting tilt in the effective potential will shift the distribution of stars relative to the DM halo.
- Moreover, some stars can escape and will end up travelling ahead of the DM halo.
- Both of these effects can lead to a separation between the peak of the distribution of stars and the centroid of the DM halo.

Results frequent interactions

Simplified numerical simulation: Trace the motion of a set of test particles (DM and stars) in a time-dependent gravitational potential.



- As expected, the peaks of the two distributions are slightly shifted.
- The dark matter halo retains its form.
- However the tail of the distribution of stars is enhanced in the forward direction due to stars that have escaped from the gravitational potential of the subhalo.

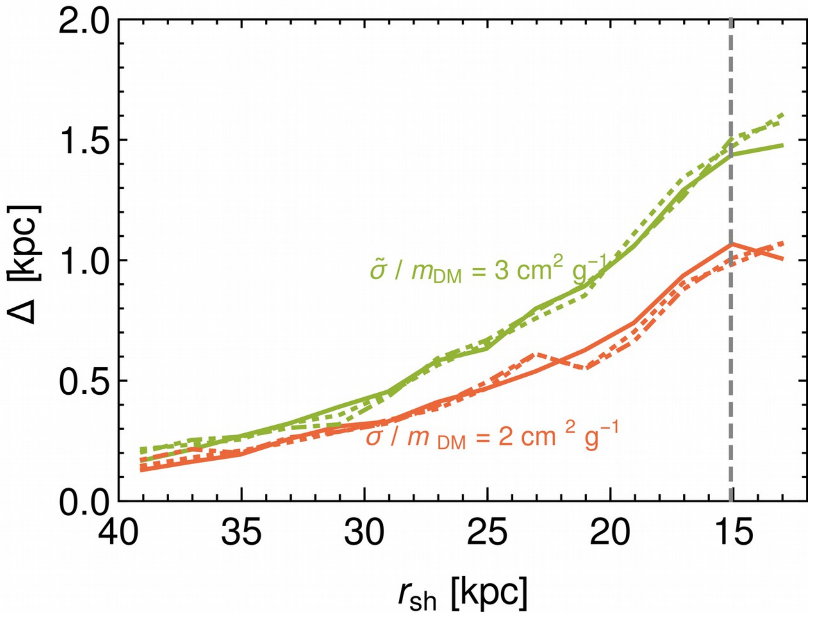
What is the observable separation?

There are some subtleties as to how to define the separation

It is not sensible to just calculate the subhalo position including all initially bound particles, because particles that have escaped would strongly bias the centroid position.

It is also not sensible to just determine the peak position, which (for the DM distribution) cannot be obtained observationally.

For a realistic estimate we include only particles within the iso-density contour containing 20% of the total mass of the DM subhalo (corresponding roughly to the inner 4 kpc) and some alternatives



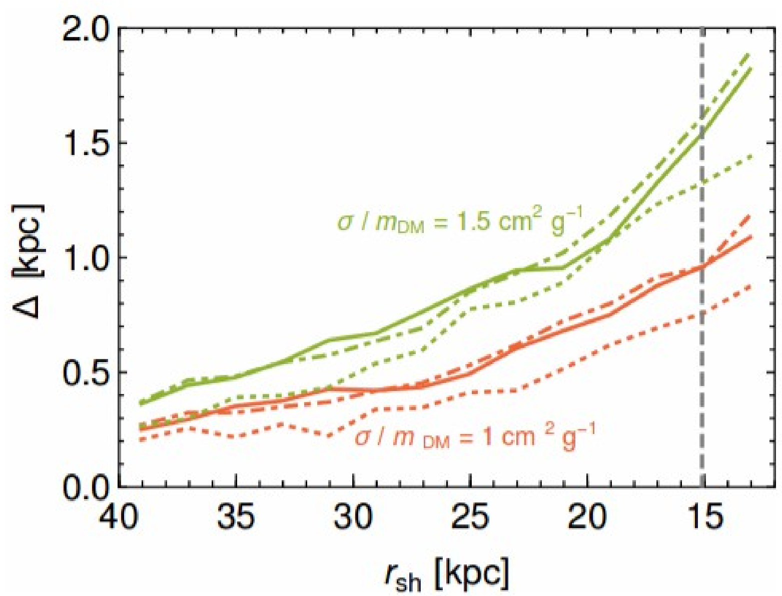
The cross section required to obtain a separation of 1.5 kpc is about

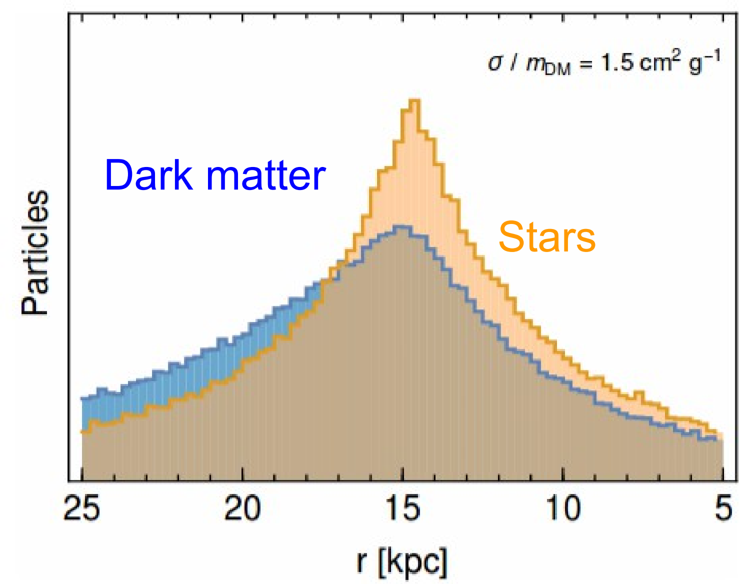
$\sigma/m_\chi \sim 3\ cm^2/g$.

Rare self interactions

- Rare self-interactions mean that for a typical DM particle the probability for multiple scattering is negligible.
- A significant fraction of DM particles will not experience any scattering at all and therefore behave just like (equally collisionless) stars.
- On the other hand, whenever a DM scatters, it will often receive such a high momentum transfer, that it escapes from the subhalo.
- A separation between the DM subhalo and stars can also occur in this case, but the separation is due to DM particles leaving the subhalo in the backward direction or being kicked into very elliptical orbits.

Results rare self interactions





- The cross section required to obtain a separation of 1.5 kpc is about $\sigma/m_\chi \sim$ 1.5 cm^2/g.
- Note that the separation is mainly due to differences in the shapes of the two respective distributions, while the peaks of the distributions remain coincident.

What type of self interaction?

- The case of contact interactions can potentially be distinguished from the case of an effective drag force by studying in detail the shape of the DM subhalo and the relative position of the peaks of the two distributions.

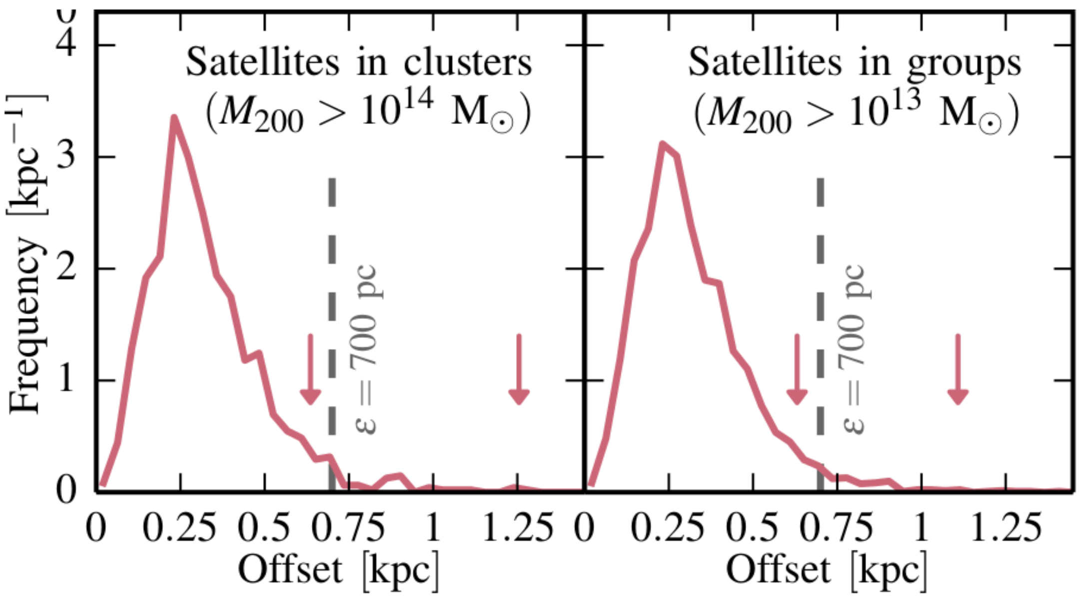
- **Contact interactions:** the DM subhalo is expected to be deformed due to the scattered DM particles leaving the subhalo in the backward direction, such that the position of the centroid depends sensitively on the centroid definition.

- **Effective drag force:** we expect the DM subhalo to retain its shape, while the distribution of stars will be both shifted and deformed.

Have we really seen DM self interactions?

To answer this need to know how likely other astrophysical explanations are

Recent hydrodynamical cosmological simulations to measure offsets between the centres of stellar and dark matter components of galaxies.



1505.05470

Offset > 1.5 kpc in less than 99.8% (random directionality)

The remaining 0.2% had recent mergers with other satellites

Summary

- Self interacting dark matter could solve some problems of the collisionless cold dark matter paradigm and can arise naturally in more complex dark sectors

- Orthogonal handle on properties of DM: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.
- Subhalos falling into galaxy clusters are a novel and interesting probe of DM self-interactions.
- Both effective drag forces (from frequent self-interactions) and rare self-interactions can lead to a separation between the DM subhalo and the stars (potentially distinguishable).
- An explanation of the separation observed in A3827 requires DM self-interactions of $\sigma/m_\chi > 1$ cm^2/g.
- Consequently, this interpretation is highly testable (if not already excluded) using other galaxy clusters.
- If interpretation true, WIMPs, axions, etc are excluded as DM candidates

Thank you!